International Journal of Mechanical and Production
Engineering Research and Development (IJMPERD)
ISSN (P): 2249-6890; ISSN (E): 2249-8001
Vol. 7, Issue 6, Dec 2017, 641-652

EFFECTS OF ULTRAVIOLET RADIATION WITH AND WITHOUT HEAT, ON THE FATIGUE BEHAVIOR OF BELOW-KNEE PROSTHETIC SOCKETS

ZAINAB YOUSIF HUSSIEN & KADHIM KAMIL RESAN

College of Engineering, Materials Engineering, AL-Mustansiriya University, Baghdad, Iraq

ABSTRACT

This work focused on below-knee (BK) prosthetic sockets, which have gained wide application due to the increasing number of patients with BK amputation as a result of terrorist attacks and life-threatening situations in war-stricken areas, such as Iraq. Given the hot weather in Iraq, a number of studies have explored the effects of temperature on specific socket materials. The current study attempts to explain the effects of ultraviolet (UV) radiation, in combination with temperature, on the properties of socket materials. In the experimental work, two sets of specimens, namely, Material A (acrylic resin and hardener reinforced with 10 layers of perlon, and Material B (acrylic resin and hardener reinforced with 8perlon layers and2carbon fibers), were manufactured using a vacuum technique. The socket materials were subjected to tensile testing to obtain their mechanical properties. The failure characteristics of sockets were determined by fatigue testing using a machine (alternating bending fatigue) manufactured specially for this purpose. Fatigue testing was carried out in four different exposure environments (at room temperature with and without UV radiation and at 50 °C with and without UV radiation). Interface pressure between the stump and the socket was measured using an F-socket device. In the numerical study, a prosthetic socket was drawn by using AUTOCAD software. Finite element technique (ANSYS-Workbench 15) was used to analyze and evaluate the fatigue characteristics by observing the maximum stress, total deformation, and safety factor. Results show that the modulus of elasticity (19.7), ultimate tensile strength, and yield stress of socket material sunder group B were superior to those of group A. The material with carbon fiber reinforcement showed the highest fatigue limit and safety factor values (5.0638, 4.6565, 5.0424, and 4.4613). However, the combined effect of temperature and UV radiation decreased the safety factors and rendered the materials of group A as unsafe. The equivalent von Mises stress reached a maximum of16.9MPaand was centered at the anterior side of the tibia bone.

KEYWORDS: Transtibial Amputation, Prosthetic Socket, Fatigue, Ultraviolet Radiation-Socket & ANSYS

Received: Nov 17, 2017**; Accepted:** Dec 04, 2017**; Published:** Dec 12, 2017**; Paper Id.:** IJMPERDDEC201772

INTRODUCTION

Amputations of lower limbs result from increasing vascular diseases, birth defects, and tumors. Suitable and adaptable prosthetic devices are crucial in how amputees relate to society, their families, and the workplace. The fundamental classifications for lower limb prostheses are based on amputation height. These classifications are transfemoral and transtibial (TT) prostheses. Below-knee (BK) prosthesis comprises a prosthetic foot, pylon, and TT socket (Figure (1)). [1]

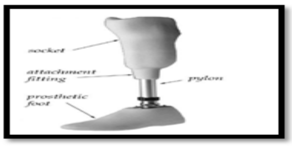


Figure 1: Below Knee Prosthetic Components. [2]

Original Article

The socket is an important part of any prosthetic limb because of its function as the interface between the prosthetic components and the stump. Biomechanical knowledge on the mutual behavior of the stump, socket, and attachment leads to the improvement of prosthetic functions. Improvement in the function and provided comfort of the prostheses leads to increased satisfaction among patients[3].Owing to the increase in the number of people who lose their limbs due to health problems and injuries caused by wars and terrorist attacks (Figure (2)), the use of prostheses has increased, along with the consideration of the suitability and capability of their parts to perform target functions, as well as their accessibility and affordability [4].Advances in prosthetics have been achieved as a result of advances in other fields.

The material and mechanical properties of prosthetic sockets have been studied by numerous investigators. The effects of temperature in hot climate countries on sockets manufactured from laminate substances during walking was studied by **Mustafa T. Ismail et al. [5].** As temperature increases, the mechanical properties of sockets decrease over a period of time because of the creep phenomenon, whose interaction with fatigue results in socket failure. **Ramesh K. et al. [6]** manufactured BK prosthetic sockets from laminated composite materials by using a vacuum molding technique; the matrix epoxy was reinforced with five types of laced fibers (carbon, glass, perlon, a glass–carbon hybrid, and a glass–carbon hybrid with silica. **Ikram R. Abd Al-razaq et al. [7],** investigated the sockets of lower limb prosthetics fabricated using a new method called modular socket system, which involves the use of direct lamination on the stumps of patients; the team subjected the socket materials to tensile stress and creep(50 °C) and determined the socket failure characteristics at room temperature and high temperature (50 °C) by fatigue testing.

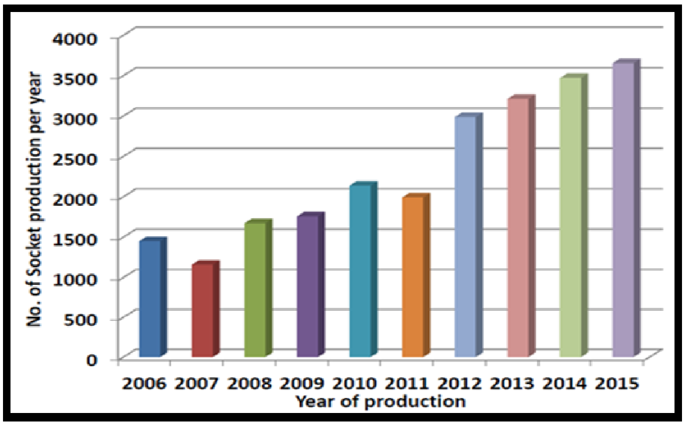


Figure 2: Production of Socket in Iraq During Recent Years.[8]

EXPERMENTAL WORK

DESIGN AND MANUFACTURE OF FATIGUE TESTING MACHINE

A fatigue device was designed and manufactured to obtain the curve of stress (S)–number of cycles (N) for the materials of prosthetic sockets with and without the effects of heat and ultraviolet (UV) radiation. The fatigue device was operated using a control board containing controlling and measuring devices that work collectively to adjust motor speed, record the cycles of reciprocating mechanisms, and save the last readings during specimen failure or power outage. An electric motor was mounted on one end of a heavy base plate. The motor shaft carried a pulley with a V-belt drive to a counter shaft. The counter shaft was encased in a substantial bearing cylinder and equipped with an eccentric drive mechanism. From one end, the shaft suspended an aluminum pulley, which was driven by the motor of a V-belt. At the other end, the shaft supported an aluminum bush. The container is supplied with an air heater to keep a constant

temperature around the specimen to study the heat effect and ultraviolet (UV.C) fluorescent lamp (Figure (3)).

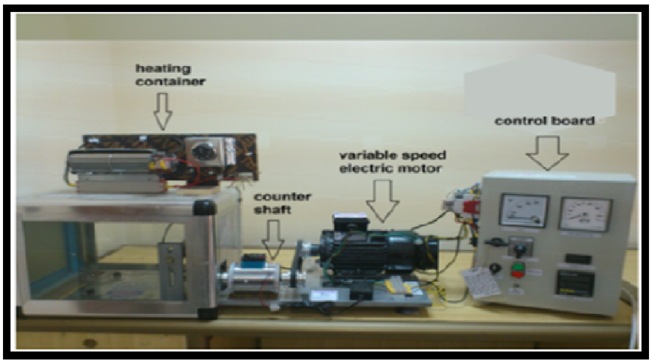


Figure 3 Fatigue Testing Machine

PROSTHETIC SOCKET MANUFACTURING BY VACUUM TECHNIQUE

Numerous manufacturing methods have become accessible to patients who require the best mechanical properties and seek to address their personal clinical needs. One of the most widely available and traditional socket manufacturing methods is the vacuum technique (Figure (4)).

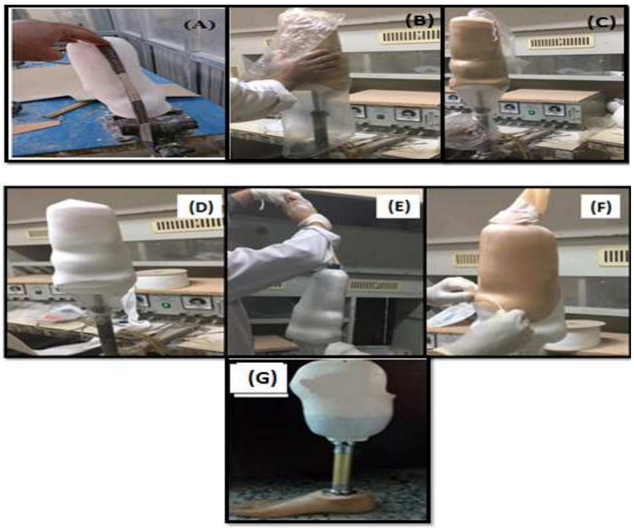


Figure 4: Manufacturing Steps of the Composite Socket

EXPERIMENTAL PROCEDURE

To define the mechanical properties of sockets, we manufactured specimens using a process similar to that employed in the production of prosthetic sockets. Materials were used, shown in Table (1).The following steps were observed

- A gypsum mold with dimensions of 20, 10, and 10 cm was fabricated (Figure (5A)).
- Polyvinyl alcohol (PVA) film was applied on the mold, and vacuum was applied to the PVA film (Figure (5B)).
- Various layers of reinforcement, namely, group A (10 layers of perlon) and group B (8 layers of perlon and 2 layers of carbon fiber), were applied (Figure (5C)).
- Covering the mold with a second PVA bag after put talcum powder inside it to facilitate dressing. This PVA bag

is open at the top to accept the liquid plastic (lamination resin and hardener) (Figure 5D, E).

- Acrylic resins with hardener were stirred slowly for 1–2 min. The amounts of resin and powder hardener used in the two carbon layers were 475 mL and 15.3 g, respectively, whereas those used in the 10 layers of perlon were 500 mL and 17 g, respectively. The acrylic material is shown in Figures (5F, 5G).
- After resin curing, the obtained cubic composite material was cut into the required specimen dimensions (Figures (5H, 5I)).

Figure 5: Vacuum Process of Samples Fabrication

Table 1: Materials used in Manufacturing Process

Groups	Reinforcement	Matrix	Method
A	10 layers of perlon	Lamination resin(acrylic,500ml)With hardener(17g)	Vacuum technique
B	8 perlons layers +2 layer of carbon fiber	Lamination resin(acrylic,475ml)with hardener(15.3g)	Vacuum technique

Preparation of Specimens and Testing

Samples were cut using numerical control machines. A mold was prepared for cutting samples for fatigue and tensile tests (ASTM D6380 Type I)**.**

Tensile Test

This test was conducted at room temperature according to the ASTM D-638 Type I. A Tinius Olsen device was used, to determine yield strength (σy), yield point elongation, tensile strength (UTS), elastic modulus (E), and elongation (ΔL%). The tensile properties may vary with specimen preparation, speed (feed speed = 5 mm/min), and testing environment [9].

Fatigue Test

The specimens were subjected to deflection perpendicular to their axes at one side. The other side was fixed, and bending stresses were developed by using alternating bending fatigue with constant amplitude.

Interface Pressure Distribution and Numerical Analysis

The interface pressure between the stump and the socket was measured by using an F-socket device consisting of sensors (Figure (6)).

After the dimensions of the socket were obtained, the socket was drawn by using AUTOCAD software (version 2014). Meshing was applied to the model, which was then attached at the end of the socket. Pressure was distributed to particular positions by using ANSYS software (Figure (7)).

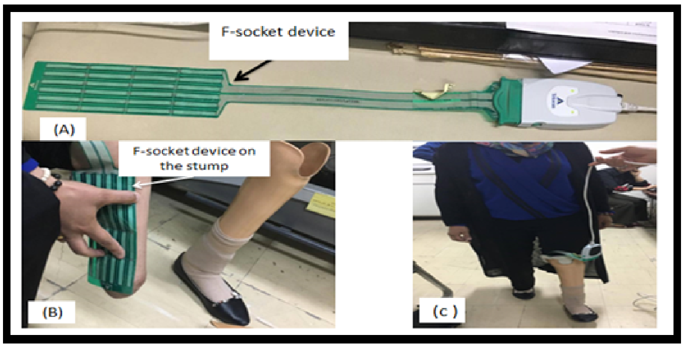


Figure 6: F-Socket Device with Patient

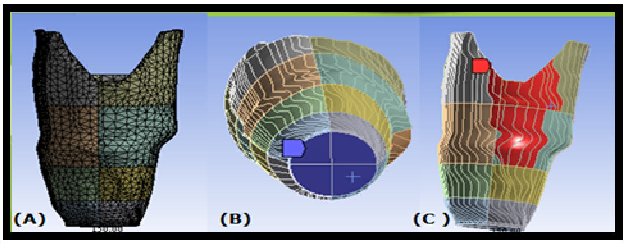


Figure 7: Steps of Numerical Part by using ANSYS

RESULTS AND DISCUSSIONS

Tensile Test

Table (2) shows that, the socket material from group A exhibited the lowest modulus of elasticity (8.3 MPa), whereas the socket material from group B exhibited the highest modulus of elasticity (19.7 MPa), because of the presence of the carbon fiber material. The same table shows that, group A presented higher ultimate tensile strength and lower yield stress compared with group B.

Table 2: Results of Tensile Properties of Socket Materials

Group	Yield stress (σy) MPa	Ultimate Tensile strength	Young modulus (E) GPa
A	58.2	67.8	8.3
B	147.6	161	19.7

Fatigue Test

The S–N diagram is often used to define the fatigue failures of materials. The S–N curves for the composite materials of group A with and without the effects of heat and UV radiation are shown in Figure (8).

The results of the two classes of laminates indicate that reinforcement type exerts a considerable effect on fatigue resistance. As shown in Figure (9), carbon fiber reinforcement provided the highest fatigue limit because of its high Young's modulus I and ultimate tensile strength in comparison with the perlon reinforcement, which provided the lowest fatigue limit. The effects of temperature on group B composite materials were minimal because carbon fiber materials exhibit high chemical and thermal stability, as well as superior fatigue properties. By contrast, temperature strongly affected group A materials because, perlon features low thermal stability. Group B presented the lowest heat and UV radiation effects due to the presence of carbon fiber. This material can achieve sustained performance under harsh and changing environmental conditions, including varying temperature, UV radiation, thermal cycling, and mechanical fatigue conditions. Their combination with high ambient temperature is responsible for the decreased lifetime of products. A small increase in solar UV levels can markedly accelerate deterioration in locations with high ambient temperature.

The synergistic effect of high temperature and solar UV radiation is responsible for the rapid degradation of materials [10].

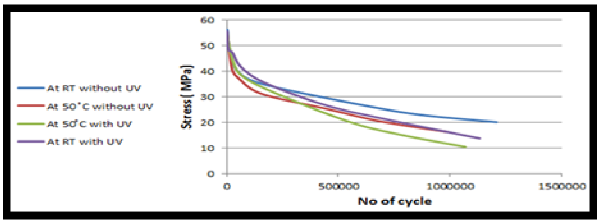


Figure 8: S-N Curves of Group (A).

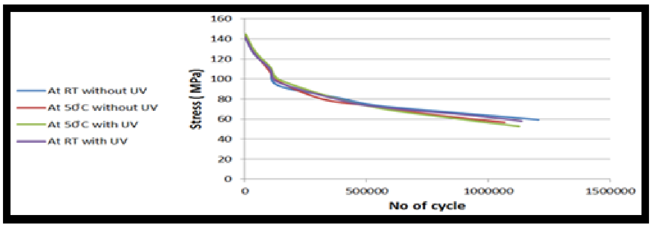


Figure 9: S-N Curves of Group (B)

NUMERICAL ANSYS RESULTS

Socket interface designs can be divided into four basic categories (anterior, posterior, lateral, and medial) according to their respective weight-bearing characteristics. For analyzing the motion system of patients, interface pressures between the residual limb and the socket were recorded as each participant walked at a self-selected speed.

The results of the applied pressure during the gait cycle of the patients obtained using the F-socket software are shown in Figures (10), (11), (12), and (13). A difference was noted between the middle and late stances, and an increase in interface pressure was observed during the late stance for each zone of the anterior, medial, posterior, and lateral sensor arrays.

According to the results obtained with the ANSYS workbench15 for group A, the safety factor decreased with the temperature effect. This decline became increasingly serious with the effects of UV radiation and temperature (Table (4)). Group B showed a more substantial decrease in safety factor than group A. These results were attributed to the use of carbon fiber materials.

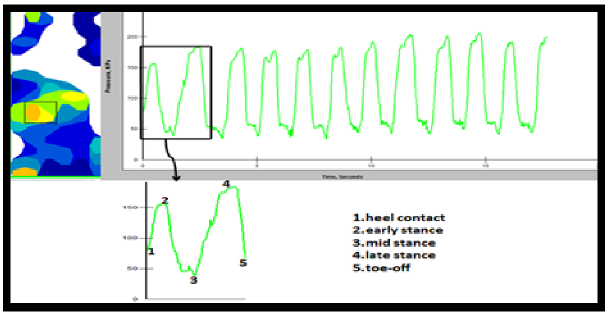


Figure 10: Pressure Result at Anterior Part

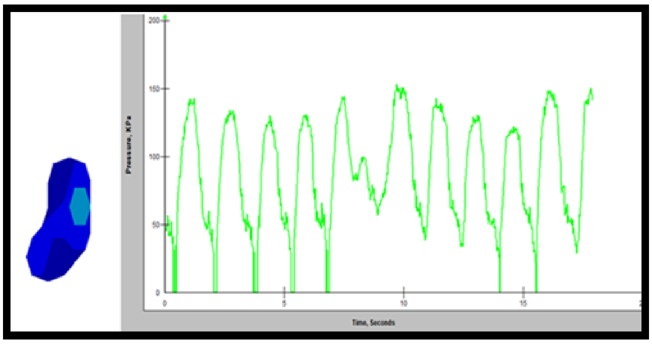


Figure 11: Pressure Result at Posterior Part

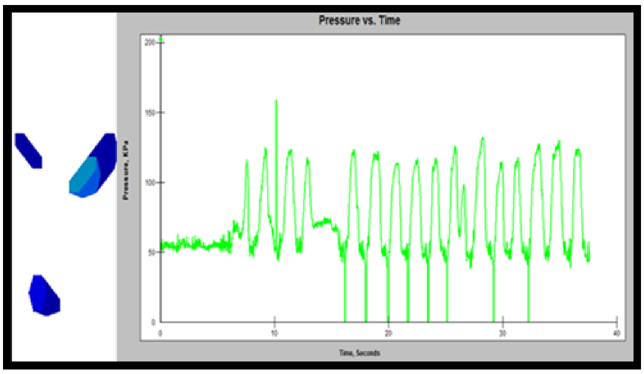


Figure 12: Pressure Result at Lateral Part

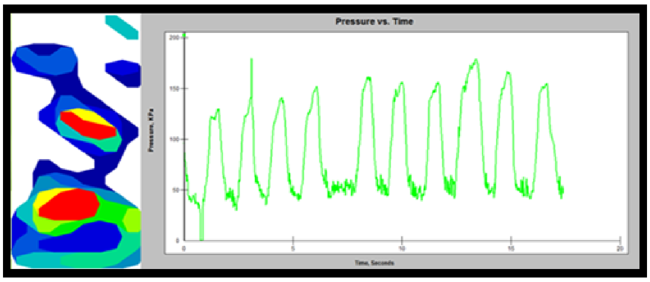


Figure 13 Pressure Result at Medial Part.

Table 3: Location and Maximum Pressure Values of Heel Strike Generated in the Socket

Location	Maximum Pressure Value (Kpa)
Anterior	203
Posterior	152
Lateral	130
Medial	180

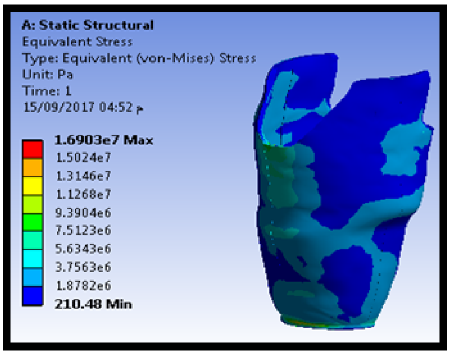


Figure 13: Stress Distribution for Tow Type of Socket Material

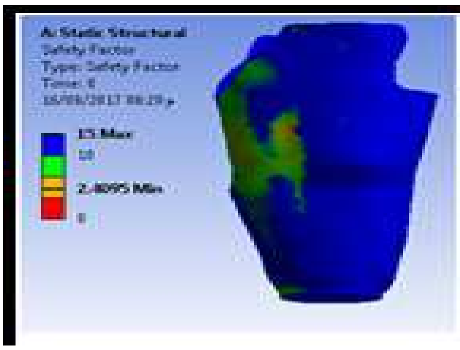
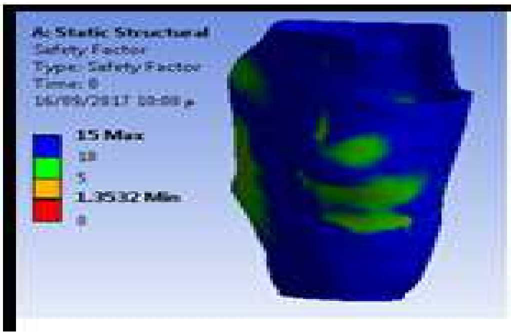


Figure 14: Safety Factor For Group A At RT **Figure 15: Safety Factor For Group B At RT**



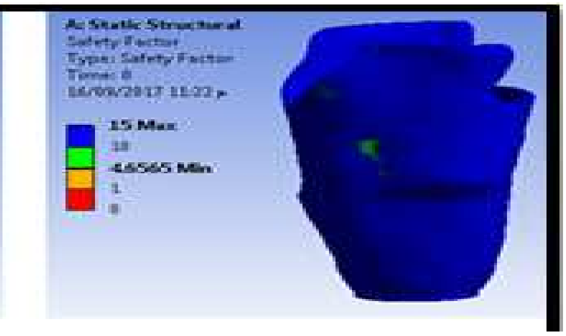
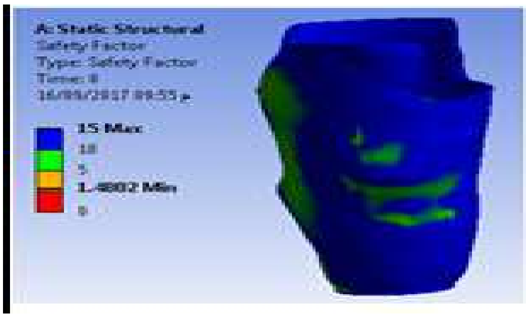


Figure 16: Safety Factor of Group A At 50^0c Without Uv

Figure 17: Safety Factor of Group B at 50^0c Without UV



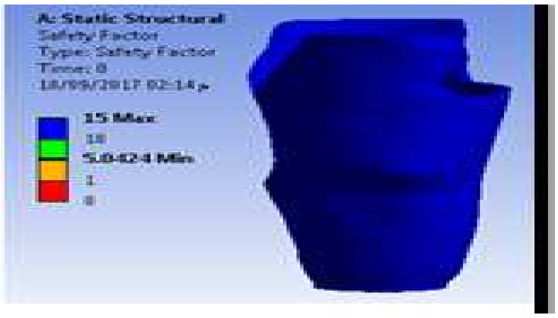
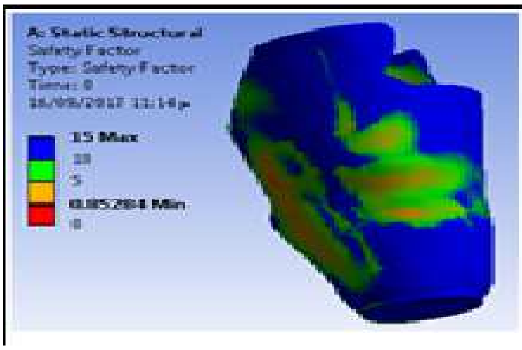


Figure 18: Safety Factor of Group A at RT With UV

Figure 19: Safety Factor OF Group B at RT With UV



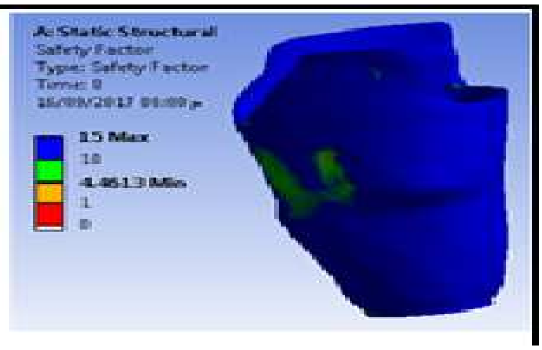


Figure20: Safety Factor of Group A at 50^0c Without Uv

Figure 21: Safety Factor of Group B at 50^0c Without UV

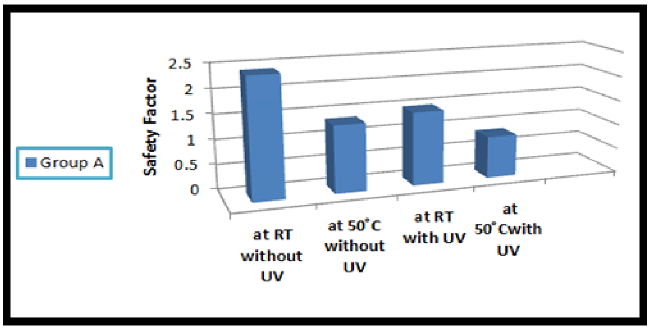


Figure 22: Safety Factor Values of Group (A)

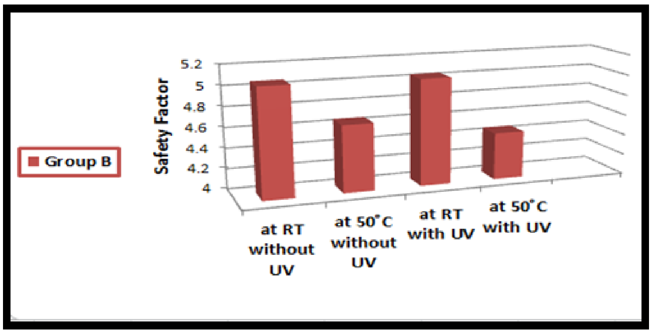
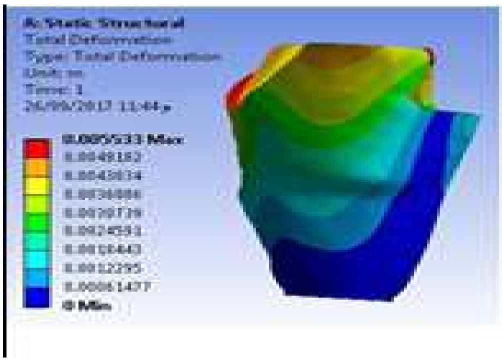


Figure 23: Safety Factor Values of Group (B)



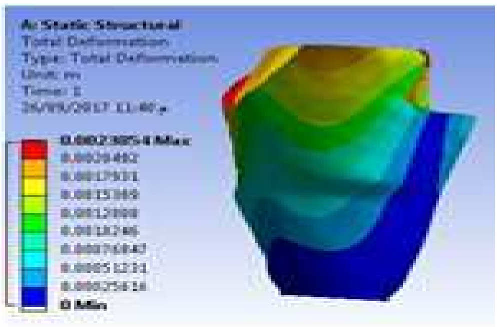


Figure 24: Deformation of Group A Figure 25: Deformation of Group B

Table4: Comparison the Mechanical Properties of Groups

Groups	Safety Factor At RT Without UV	Safety Factor At 50℃ Without UV	Safety Factor At RT With UV	Safety Factorat 50℃ With UV	Deformation
A	safe	safe	safe	unsafe	comfortable
B	safe	safe	safe	safe	comfortable

CONCLUSIONS

- Socket materials under group A are more effective than those under group B.
- The effects of UV radiation and heat on traditional sockets (group A) cause failure.
- Carbon materials are minimally affected by temperature and UV radiation.

ACKNOWLEDGEMENTS

The author would like to acknowledge: (Al-Mustansiriyah University – materials engineering dep. Labs),(Baghdad Artificial Limb Center),(Al-Nahrain University_ Engineering college_ Department of prosthetic and orthotic)Baghdad –Iraq for the provision of facilities.

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